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First Named Inventor **WITOLD KULA**	
Title **IMPROVED SPIN VALVE MAGNETIC PROPERTIES WITH OXYGEN-RICH NIO UNDERLAYER**	

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PATENT APPLICATION

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IMPROVED SPIN VALVE MAGNETIC PROPERTIES WITH
OXYGEN-RICH NiO UNDERLAYER

INVENTOR
10   Witold Kula

FIELD OF THE INVENTION

This invention relates generally to a magnetoresistive sensor.
More particularly, it relates to improved spin valve magnetic
15   properties with an engineered NiO underlayer.

BACKGROUND ART

A spin valve or a giant magnetoresistive (GMR) sensor detects
magnetic field signals through the resistance changes of a
20   read element, fabricated of a magnetic material, as a function
of the strength and direction of magnetic flux being sensed by
the read element. A conventional magnetoresistive sensor
operates on the basis of the anisotropic magnetoresistive
(AMR) effect in which a component of the read element
25   resistance varies as the square of the cosine of the angle
between the magnetization in the read element and the
direction of sense current flow through the read element.
Recorded data can be read from a magnetic medium, because the
external magnetic field from the recorded magnetic medium (the
30   signal field) causes a change in the direction of
magnetization in the read element, which in turn causes a
change in magnetoresistive ratio ($\Delta R/R$) in the read element.

A spin valve or a GMR sensor has been identified in which the resistance between two uncoupled ferromagnetic layers is observed to vary as the cosine of the angle between the magnetizations of the two layers and is independent of the direction of current flow. The latter spin valve produces a magnetoresistance that, for selected combinations of materials, is greater in magnitude than the AMR. Typically, the higher GMR ratio ($\Delta R/R$) results in higher amplitude and better overall performance of the spin valve recording heads.

Typically, a conventional spin valve includes a ferromagnetic free layer, a ferromagnetic pinned layer, which is exchange-coupled with an antiferromagnetic (AF) layer, and a spacer layer located between the free layer and the pinned layer. Often an underlayer of metal, such as Ta, Zr, and Cu, or metal oxide, such as NiO and NiMnOx, is applied to enhance the $\Delta R/R$ ratio of the spin valve. Antiferromagnetic layers shift the hysteresis loops of ferromagnetic films away from the zero field axis. The shift brings the most sensitive part of the magnetoresistive loop close to zero field.

However, the underlayers of spin valves made by the prior art do not optimize the $\Delta R/R$ ratio of the spin valve. Furthermore, the spin valves of the prior art do not optimize the pinning strength, which is the external field applied to a spin valve enough to unpin the magnetization of the pinned layer. Typically, the higher the pinning field is, the better is the spin valve's performance. The desirable value of pinning strength is typically above 400 Oe. The same mechanisms that increase spin valve $\Delta R/R$ often lower its pinning strength H_{ua}. Spin valves of the prior art cannot balance high values of $\Delta R/R$ and high pinning strength to improve the performance of spin valves.

There is a need, therefore, for a spin valve structure that improves spin valve magnetic properties.

OBJECTS AND ADVANTAGES

5   Accordingly, it is a primary object of the present invention to provide a structure for a spin valve that:

1) can optimize the GMR ratio ($\Delta R/R$) of the spin valve;

10   2) can optimize the pinning strength; and

3) can balance the GMR ratio and the pinning strength.

These and other objects and advantages will be apparent upon
15   reading the following description and accompanying drawings.

SUMMARY

These objects and advantages are attained by a spin valve that detects an external magnetic field with the aid of non-stoichiometric oxygen-rich nickel oxide underlayers containing
20   substantially more than 50 atomic % (at. %) of oxygen, typically 55 at.% or more.

A spin valve typically includes a ferromagnetic free layer, a
25   ferromagnetic pinned layer, and an antiferromagnetic layer coupled with the ferromagnetic pinned layer. A nonmagnetic spacer layer is disposed between the ferromagnetic free layer and the ferromagnetic pinned layer. The spin valve further includes an underlayer to enhance the giant magnetoresistive
30   ratio ($\Delta R/R$). In accordance with a first embodiment of the present invention, the underlayer of a spin valve is an oxygen-rich nickel oxide layer, which is made using reactive sputtering of a nickel target in an oxygen-rich atmosphere consisting substantially of pure oxygen and inert gases,

typically argon gas. An oxygen/argon ratio higher than 1:10 typically produces an underlayer of oxygen-rich nickel oxide with more than 55 at.% of oxygen that improves the $\Delta R/R$ value of a spin valve. The thickness of the oxygen-rich nickel oxide

5   layer is typically between about 20Å (2nm) and about 400Å (40nm). Additional enhancement of the $\Delta R/R$ value of a spin valve is achieved by reducing the total pressure of the atmosphere consisting of pure oxygen and argon during the oxygen-rich nickel oxide film formation. This spin valve

10   structure provides a value of $\Delta R/R$ between about 7% and about 9%.

According to a second embodiment of the present invention, the underlayer of a spin valve is a pseudo-dual layer, in other words the spin valve has two adjacent nickel oxide underlayers

15   with a total thickness between about 20Å and about 400Å. Either or both of these two nickel oxide underlayers are oxygen-rich nickel oxide layers. Two nickel oxide underlayers are made using a sputtering method similar to the method

20   described in connection with the first embodiment. The oxygen content differs between the two nickel oxide underlayers. Proper selection of the oxygen content and thickness of each of the two nickel oxide underlayers results in a higher $\Delta R/R$ ratio with a given pinning strength (H_{ua}), or higher H_{ua} with a

25   given $\Delta R/R$ ratio than those achieved with a spin valve including only one oxygen-rich nickel oxide underlayer. This spin valve structure provides a value of $\Delta R/R$ between about 7% and about 9%.

30   Since the increase in $\Delta R/R$ ratio is generally accompanied by decrease in the pinning strength H_{ua}, a second embodiment of the present invention is particularly useful in balancing the $\Delta R/R$ and H_{ua} values, in cooperation with other factors

increasing H_{ua}, such as the selection of materials for pinned and pinning layer in a spin valve.

According to a third embodiment of the present invention, spin valves of the types depicted in the first and second embodiments are incorporated in read/write heads used in disk drive systems. A disk drive system includes a magnetic recording disk, the read/write head, an actuator for moving the read/write head across the magnetic recording disk, and a motor for spinning the disk.

BRIEF DESCRIPTION OF THE FIGURES

Fig. **1** is a cross-sectional schematic diagram of a spin valve with an oxygen-rich nickel oxide underlayer, according to an embodiment of the present invention; and

Fig. **2** is a cross-sectional schematic diagram of a spin valve with two nickel oxide underlayers, according to another embodiment of the present invention; and

Fig. **3** is a schematic diagram of a disk drive system according to a third embodiment of the present invention.

DETAILED DESCRIPTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following embodiments of the invention are set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

Fig. 1 is a cross-sectional schematic diagram of a spin valve **100**, according to an embodiment of the present invention. Spin valve **100** includes a ferromagnetic free layer **106** contacting a

nanolayer **108**, a ferromagnetic pinned layer **112**, and an antiferromagnetic (AF) layer **114** contacting with ferromagnetic pinned layer **112**. A first nonmagnetic spacer layer **110** is disposed between nanolayer **108** and ferromagnetic pinned layer **112**. Spin valve **100** further includes an underlayer **102**, and a second nonmagetic spacer layer **104** disposed between ferromagnetic free layer **106** and underlayer **102**. A protective cap layer **116** is located on top of spin valve **100**, contacting with AF layer **114**. Spin valve **100** is deposited on top of a substrate **118**.

Cap layer **116** typically includes Ta. AF layer **114** is typically made of a material containing Mn. Ferromagnetic pinned layer **112** typically includes Co or Cobalt alloys. Nonmagnetic spacer layers **110** and **104** are typically made of Cu, Ag, Au or their alloys. Nanolayer **108** typically includes Co or cobalt alloys. Ferromagnetic free layer **106** typically includes a material containing Ni, Fe, Co or alloys of Ni, Fe and Co such as NiFe, NiCo, NiCoFe and FeCo. Underlayer **102** is typically made of a metal, such as Ta, Zr or Cu, or metal oxide, such as NiO or NiMnO. Substrate **118** is typically made of Al_2O_3-TiC.

To improve the ΔR/R ratio of spin valve **100**, underlayer **102** is made of oxygen-rich nickel oxide, and has a thickness of between about 20Å (2nm) and about 400Å (40nm). Oxygen-rich nickel oxide underlayer **102** is made using reactive sputtering of a nickel target in an oxygen-rich atmosphere consisting substantially of pure oxygen and an inert gas, typically argon. For the typically used gas pressure of about 2mTorr and nickel oxide film growth rate of about 0.5Å/s, the oxygen/argon ratio must be higher than 1:10 to achieve an oxygen-rich nickel oxide underlayer **102** that provides a ΔR/R ratio of spin valve **100** between about 7% and about 9%. The

content of oxygen in oxygen-rich nickel oxide underlayer **102** is typically between about 55 at.% and about 65 at.%.

An example is given below to show the effect of the oxygen-rich nickel oxide underlayer on the $\Delta R/R$ ratio. A spin valve with a complete structure denoted by NiO/Cu/NiFe/CoFe/Cu/Co/NiMn/Ta, includes an underlayer of NiO, a first nonmagnetic spacer layer of Cu, a ferromagnetic free layer of NiFe, a nanolayer of CoFe, a second nonmagnetic spacer layer of Cu, a ferromagnetic pinned layer of Co, an AF layer of NiMn, and a cap layer of Ta. Table 1 below shows the improvement of the spin valve GMR ratios ($\Delta R/R$) with nickel oxide underlayers formed in increasingly oxygen-rich atmospheres. In table 1, the $\Delta R/R$ ratios are optimized with desirable values of pinning strengths H_{ua}, which are the external fields applied that are enough to unpin the magnetization of the pinned layer, and the coupling strengths H_f, which shift the hysteresis loops of the ferromagnetic free layer away from a zero field axis.

TABLE 1

Oxygen flow(sccm)	Argon flow (sccm)	$\Delta R/R$ (%)	H_f (Oe)	H_{ua} (Oe)
10	50	7.9	11.9	780
30	30	8.5	9.6	701
50	10	8.7	9.3	598

As shown in table 1, the value of $\Delta R/R$ increases as the oxygen/argon ratio increases. Additional enhancement of the oxygen-rich NiO properties as an underlayer is achieved by reducing the total pressure of the oxygen-rich atmosphere during the oxygen-rich NiO film formation. For example, with an oxygen/argon flow ratio of 20sccm/40sccm respectively, the

ΔR/R value increases from about 8.2% to about 8.5% as the total pressure is reduced from about 2mTorr to about 1mTorr.

Fig. 2 is a cross-sectional schematic diagram of a spin valve **200** according to a second embodiment of the present invention. The basic structure of spin valve **200** is similar to the basic structure of spin valve **100** of Fig. 1. Spin valve **200** includes a ferromagnetic free layer **206** contacting a nanolayer **208**, a ferromagnetic pinned layer **212**, and an antiferromagnetic (AF) layer **214** contacting ferromagnetic pinned layer **212**. A first nonmagnetic spacer layer **210** is disposed between nanolayer **208** and ferromagnetic pinned layer **212**. Spin valve **200** further includes a first underlayer **201**, a second underlayer **202**, and a second nonmagetic spacer layer **204** disposed between ferromagnetic free layer **206** and first underlayer **201**. A cap layer **216** is located on top of spin valve **200**, contacting AF layer **214**. Spin valve **200** is deposited on top of a substrate **218**. Typically, the materials of each layer in spin valve **200** are similar to those of the corresponding layers in spin valve **100** of Fig. 1.

Two underlayers **201** and **202** of spin valve **200** are made of nickel oxide, and are made with a sputtering method similar to the sputtering method described above in connection with the first embodiment. Either or both of two underlayers **201** and **202** are oxygen-rich nickel oxide layers. The total thickness of two underlayers **201** and **202** is between about 20Å (2nm) and about 400Å (40nm). The content of oxygen in first underlayer **201** is typically different from the content of oxygen in second underlayer **202**. The oxygen content in first nickel oxide underlayer **201** is typically between about 50 at.% and about 60at.%, and the oxygen content in second nickel oxide underlayer **202** is typically between about 55 at.% and about 65 at.%, or vice versa.

Proper selection of the oxygen contents and thicknesses of two nickel oxide underlayers **201** and **202** of spin valve **200** leads to a higher $\Delta R/R$ ratio with a given pinning strength or a higher pinning strength with a given $\Delta R/R$ ratio than those achieved with spin valve **100** described above. The $\Delta R/R$ ratio of spin valve **200** is between about 7% and about 9%. Table 2 below illustrates a case in which both $\Delta R/R$ ratio and pinning strength H_{ua} of a spin valve are improved with a desirable value of coupling strength H_f, using spin valve structure **200** with first nickel oxide underlayer **201** having higher oxygen content than second nickel oxide underlayer **202**.

TABLE 2

Bottom NiO (lower oxygen content) underlayer thickness (Å)	Top NiO (higher oxygen content) underlayer thickness (Å)	$\Delta R/R$ (%)	H_f (Oe)	H_{ua} (Oe)
53	67	8.7	10.8	719

Since the increase in $\Delta R/R$ ratio is accompanied by a decrease in the pinning strength H_{ua} in both embodiments, this embodiment of the present invention is particularly useful in balancing the $\Delta R/R$ ratios and H_{ua} pinning strength, in cooperation with other factors increasing H_{ua}, such as the selection of materials for each spin valve layer.

Spin valves of the types described above with respect to Figs. 1 and 2 are incorporated in read/write heads used in disk drive systems **300** as shown in Fig. 3 according to a third embodiment of the present invention. The disk drive system **300**

generally comprises a magnetic recording disk **302,** a read/write head **306** containing a spin valve **301**, an actuator **304** connected to the read/write head **306,** and a motor **308** connected to the disk **302**. The motor **308** spins the disk **302** with respect to read/write head **306**. The actuator **304** moves the read/write head **306** across the magnetic recording disk **302** so the read/write head **306** may access different regions of magnetically recorded data on the magnetic recording disk **302**.

It will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.

CLAIMS

What is claimed is:

1   1. A spin valve comprising:
2   a) an antiferromagnetic layer;
3   b) a ferromagnetic pinned layer having a magnetization
4   pinned by the antiferromagnetic layer;
5   c) a ferromagnetic free layer;
6   d) a nonmagnetic spacer layer located between the free
7   layer and the pinned layer such that the pinned layer
8   controls a magnetization of the free layer; and
9   e) a first underlayer in proximity of the free layer;

    wherein the first underlayer comprises an oxygen-rich
    nickel oxide.

    2. The spin valve of claim 1, wherein the first underlayer has
        a first oxygen content sufficient to raise a
        magnetoresistive ratio ($\Delta R/R$) of the spin valve to between
        about 7% and about 9%.

    3. The spin valve of claim 1, wherein the content of oxygen in
        the first underlayer is between about 55 atomic% and about
        65 atomic%.

1   4. The spin valve of claim 1, wherein the thickness of the
2   first underlayer is between about 20Å (2nm) and about 400Å
3   (40nm).

1   5. The spin valve of claim 1, further comprising a second
2   nickel oxide underlayer adjacent to the first underlayer.

1   6. The spin valve of claim 5, wherein the second nickel oxide
2   underlayer is an oxygen-rich nickel oxide underlayer.
3

1   7. The spin valve of claim 6, wherein the content of oxygen in
2   the first underlayer is different from the content of
3   oxygen in the second nickel oxide underlayer.
4

1   8. The spin valve of claim 7, wherein the content of oxygen in
2   the second nickel oxide underlayer is between about 50
3   atomic% and about 60 atomic%.

1   9. The spin valve of claim 6, wherein the combined thickness
2   of the first underlayer and the second nickel oxide
3   underlayer is between about 20Å (2nm) and about 400Å
4   (40nm).

1   10. The spin valve of claim 6, wherein the first underlayer has
2   a first oxygen content and the second nickel oxide
3   underlayer has a second oxygen content sufficient to raise
4   the magnetoresistive ratio ($\Delta R/R$) of the spin valve to
5   between about 7% and about 9%.

1   11. The spin valve of claim 6, wherein the first underlayer has
2   a first oxygen content and the second nickel oxide
3   underlayer has a second oxygen content sufficient to
4   balance the magnetoresistive ratio $\Delta R/R$ and pinning
5   strength H_{ua}.

1   12. The spin valve of claim 11, wherein the $\Delta R/R$ ratio is
2   between about 7% and about 9%, and the value of H_{ua} is
3   between about 800 Oe and about 400 Oe correspondingly.
4

1   13. A method for making a spin valve having oxygen-rich nickel
2   oxide underlayers comprising:

3   a) providing a substrate;

4   b) sputtering a Ni target on the substrate in a sputtering

5   atmosphere consisting substantially of pure oxygen and

6   an inert gas, whereby a first nickel oxide underlayer

7   is over-oxidized;

8   c) depositing a ferromagnetic free layer on the first

9   nickel oxide underlayer;

10   d) depositing a spacer layer on the free layer;

11   e) depositing a ferromagnetic pinned layer on the spacer

12   layer; and

13   f) depositing an antiferromagnetic layer on the pinned

14   layer.

14. The method of claim 13, wherein the inert gas is argon gas.

15. The method of claim 14, wherein the oxygen/argon ratio is
greater than 1:10.

16. The method of claim 14, wherein the first nickel oxide
underlayer comprises substantially more than 50 atomic% of
oxygen.

17. The method of claim 13 further comprising:
sputtering a Ni target on the first nickel oxide underlayer
in a sputtering atmosphere consisting substantially of pure
oxygen and an inert gas, whereby a second nickel oxide
underlayer is over-oxidized.

18. The method of claim 17, wherein the inert gas is argon gas.

19. The method of claim 18, wherein the oxygen/argon ratio is
greater than 1:10.

20. The method of claim 19, wherein the total pressure of the
    sputtering atmosphere is reduced during the second nickel
    oxide underlayer formation to below 2mTorr.

21. The method of claim 20, wherein the second nickel oxide
    underlayer comprises substantially greater than 50 atomic%
    of oxygen.

22. A disk drive system comprising a read/write head containing
    a spin valve, wherein the spin valve includes:
    a)   an antiferromagnetic layer;
    b)   a ferromagnetic pinned layer having a magnetization
         pinned by the antiferromagnetic layer;
    c)   a ferromagnetic free layer;
    d)   a nonmagnetic spacer layer located between the free
         layer and the pinned layer such that the pinned layer
         controls a magnetization of the free layer; and
    e)   a first underlayer in proximity of the free layer;
    wherein the first underlayer comprises an oxygen-rich
    nickel oxide.

23. The disk drive system of claim 22, wherein the first
    underlayer has a first oxygen content sufficient to raise a
    magnetoresistive ratio ($\Delta R/R$) of the spin valve to between
    about 7% and about 9%.

24. The disk drive system of claim 22, wherein the content of
    oxygen in the first underlayer is between about 55 atomic%
    and about 65 atomic%.

25. The disk drive system of claim 22, wherein the thickness of
    the first underlayer is between about 20Å (2nm) and about
    400Å (40nm).

1 26. The disk drive system of claim 22, wherein the spin valve
2   further comprises a second nickel oxide underlayer adjacent
3   to the first underlayer.

1 27. The disk drive system of claim 26, wherein the second
2   nickel oxide underlayer is an oxygen-rich nickel oxide
3   underlayer.
4

1 28. The disk drive system of claim 27, wherein the content of
2   oxygen in the first underlayer is different from the
3   content of oxygen in the second nickel oxide underlayer.
4

1 29. The disk drive system of claim 28, wherein the content of
2   oxygen in the second nickel oxide underlayer is between
3   about 50 atomic% and about 60 atomic%.

1 30. The disk drive system of claim 27, wherein the combined
2   thickness of the first underlayer and the second nickel
3   oxide underlayer is between about 20Å (2nm) and about 400Å
4   (40nm).
5

1 31. The disk drive system of claim 27, wherein the first
2   underlayer has a first oxygen content and the second nickel
3   oxide underlayer has a second oxygen content sufficient to
4   raise magnetoresistive ratio ($\Delta R/R$) of the spin valve to
5   between about 7% and about 9%.

1 32. The disk drive system of claim 27, wherein the first
2   underlayer has a first oxygen content and the second nickel
3   oxide underlayer has a second oxygen content sufficient to
4   balance the $\Delta R/R$ ratio and pinning strength H_{ua}.

1   33. The disk drive system of claim 32, wherein the $\Delta R/R$ ratio
2   is between about 7% and about 9%, and the value of H_{ua} is
3   between about 800 Oe and about 400 Oe correspondingly.

ABSTRACT OF THE DISCLOSURE

IMPROVED SPIN VALVE MAGNETIC PROPERTIES WITH OXYGEN-RICH NiO UNDERLAYER

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for

Witold Kula

10   In a spin valve, an underlayer is made of oxygen-rich nickel oxide to enhance the giant magnetoresistive ratio ($\Delta R/R$). The oxygen-rich nickel oxide film is made using reactive sputtering of a nickel target in an oxygen-rich sputtering atmosphere consisting substantially of pure oxygen and argon gases. The total pressure of the oxygen-rich atmosphere is reduced during

15   the oxygen-rich nickel oxide film formation to additionally enhance the $\Delta R/R$ value. A spin valve including two adjacent oxygen-rich nickel oxide underlayers provides a higher $\Delta R/R$ ratio at a given pinning strength H_{ua} than does a spin valve having only one oxygen-rich nickel oxide underlayer.

Fig. 1

200

B →

216

214

212 ⊙

210

208

206

→

204

201

202

218

Fig. 2

300

304

306

301

302

308

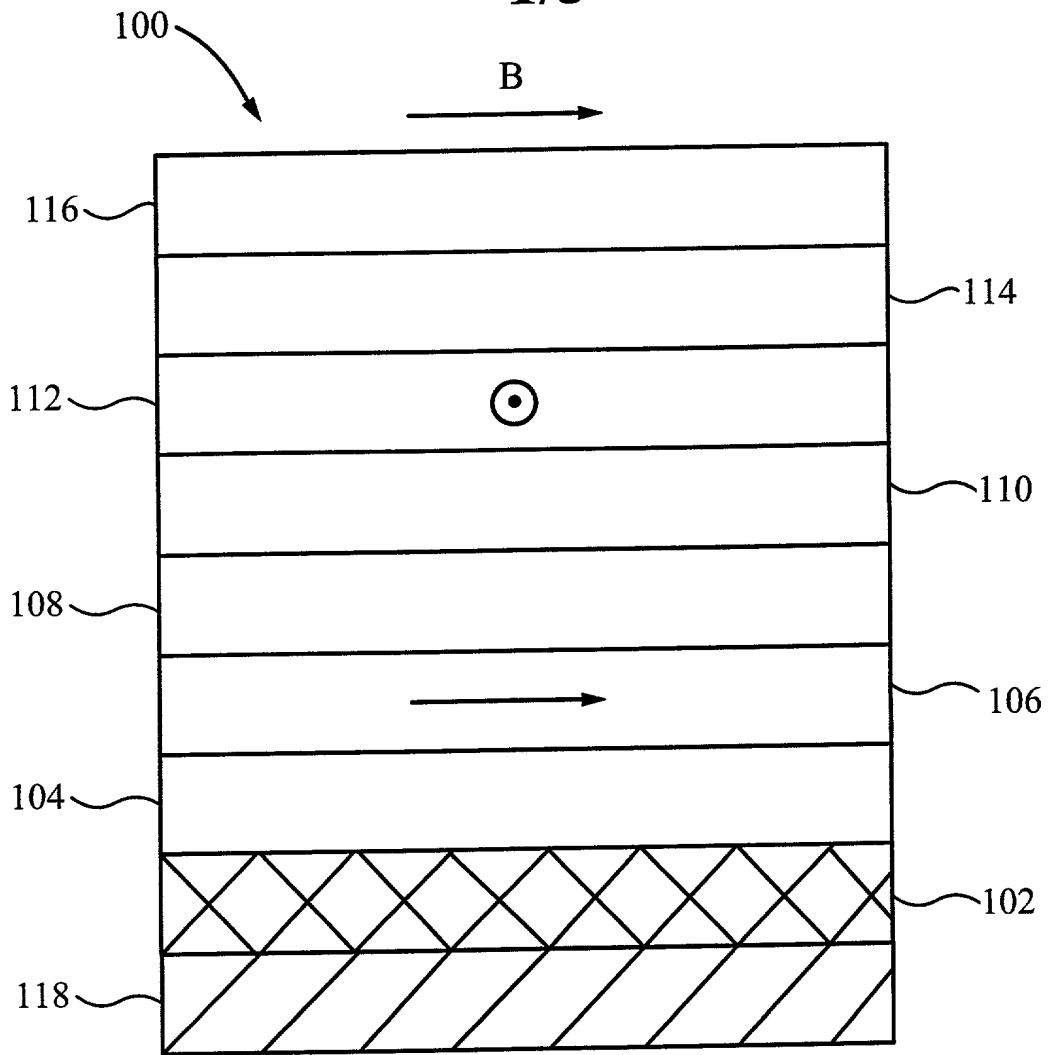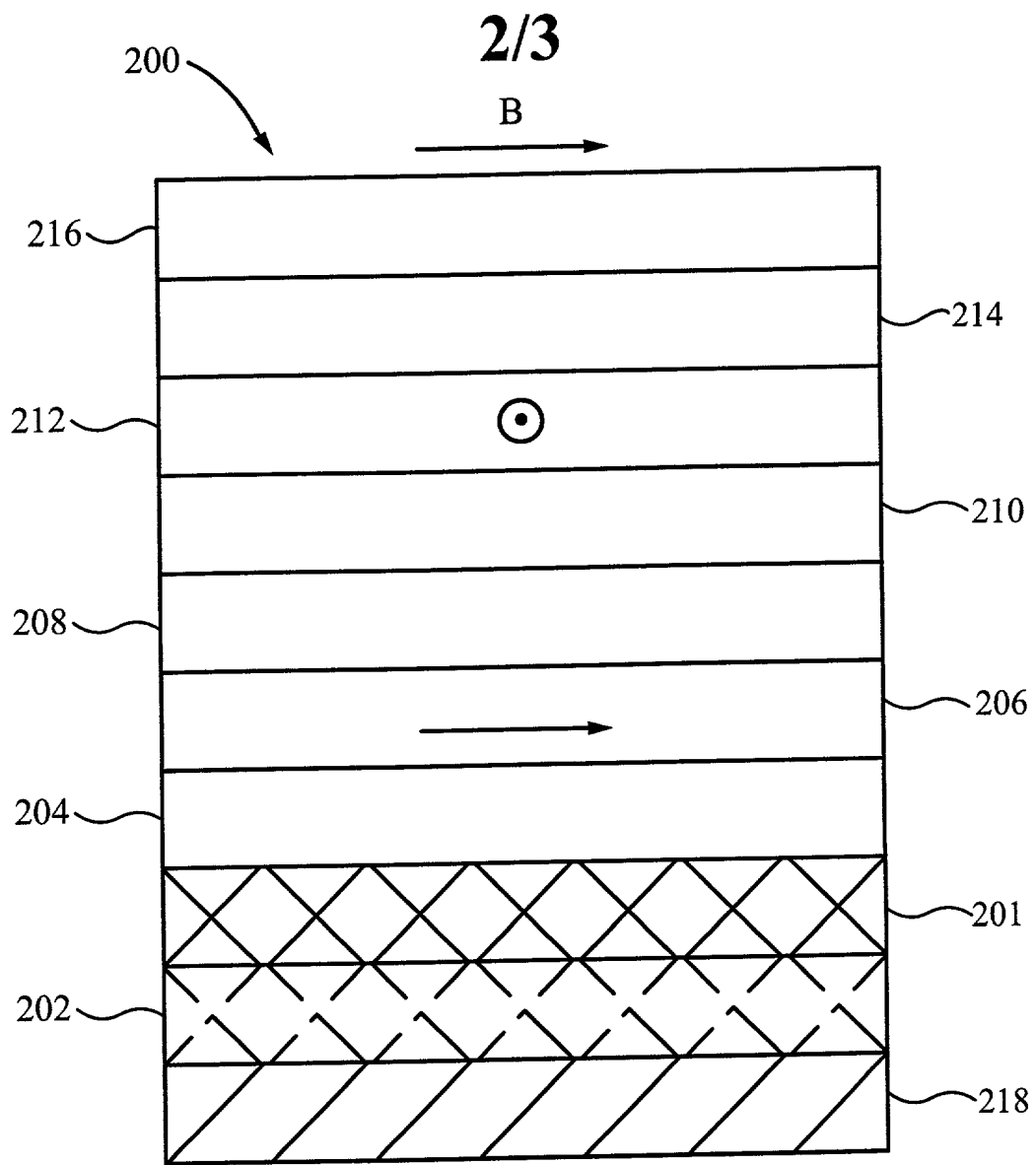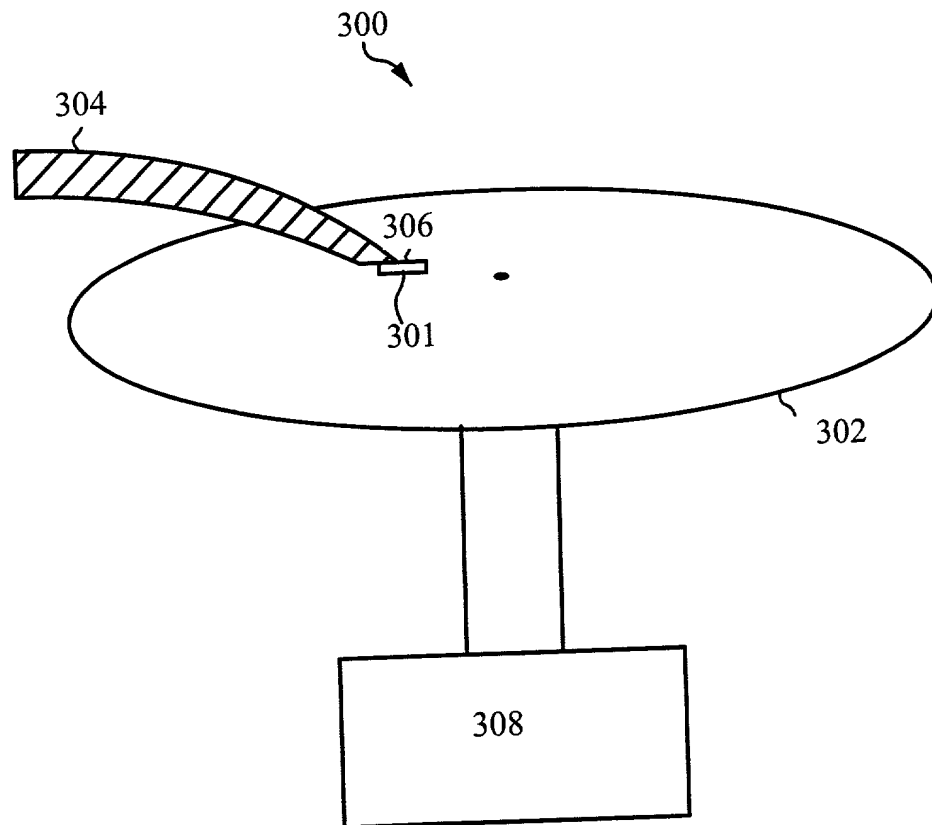**Fig. 3**

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Improved Spin Valve Magnetic Properties with Oxygen-Rich NiO Underlayer

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Docket No. **SJO9-2000-0043US1**

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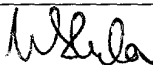   Lumen Intellectual Property Services
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